Design Study of Main Magnets for the J-PARC RCS Energy Upgrade

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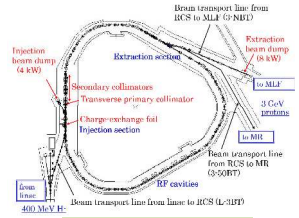
Abstract

In order to promote upgrading of J-PARC accelerator, a plan to enhance 3GeV RCS accelerator energy has been studied. When 3GeV 1MW beam from RCS is extracted into MR, a beam loss at the MR injection area exceeds the tolerance because of a space charge effect. When an extraction beam is increased to 3.4GeV, a beam loss decreases and to accept a 1MW beam at MR becomes possible. Thus a study on RCS magnets aiming at 3.4GeV.

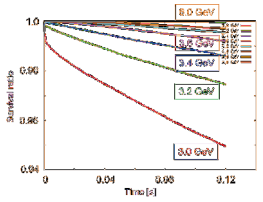
Conclusion

1. To achieve 3.4GeV extraction of dipole magnets with the existing system is difficult. An iron core was extended by 10% to design a 3.4GeV dipole magnet.
   As a result it was found out that 3.4GeV can be realized by replacing AC power supply and remodeling the control system of DC power supply.
2. For quadrupole magnets a parameter of 3.4GeV extraction falls in the maximum rated value of the power supply so the existing system can be used.
   ⇒These findings indicate that to increase RCS extraction energy to 3.4GeV is possible.
3. In addition it was studied how much enhancement of extraction energy a 3.4GeV dipole magnet can accept by allowing 10% saturation. It was found out that about 4.0GeV was possible.
   ⇒However as voltage between end terminals of magnets became 16kV and an insulation class was upgraded, it was recognized that not only a power supply source but also almost all items of the power supply system, such as a choke transformer, a resonance capacitor and power cables need to be replaced.

Background of energy enhancement



Layout of J-PARC 3GeV RCS

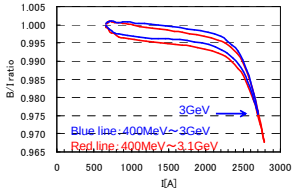


Relation between RCS extraction energy and MR beam loss

1-MW beam of 3 GeV RCS generates a large beam loss in MR due to a space charge effect. The beam loss in 3-50BT and MR would be 1.9kW and 5kW respectively. Collimators of MR exceed the tolerance value (3.5kW) and cannot accept a full beam of 1MW from RCS.
The beam power of MR is 390kW. When repetition time of MR is accelerated from 2.48s to 1.3s, a 600kW beam injection from RCS to MR produces a 750kW beam extraction of MR.

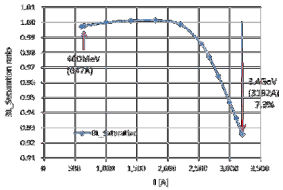
On the other hand it is also apparent that MR requires a beam operation of MW order in the near future. The relation between RCS extraction energy and MR beam loss produces a 5% beam loss at MR during a 3GeV operation.
MR can accept 1MW beam when extraction energy of RCS is larger than 3.4GeV, where a beam loss at MR becomes around 1 %. In this case MR can obtain a beam power of 1.3MW.

Margin of energy enhancement for the current magnet



Saturation property of the current and the integral field of the dipole magnet obtained from the field measurement

The result of a field measurement shows that a saturation dramatically gets worse after 2500A and it becomes almost 3% near 3GeV (2662A).



Saturation property of the current and the integral field of the dipole magnet of 3GeV

A saturation is 7.3% at 3.4GeV according to the TOSCA calculation result.

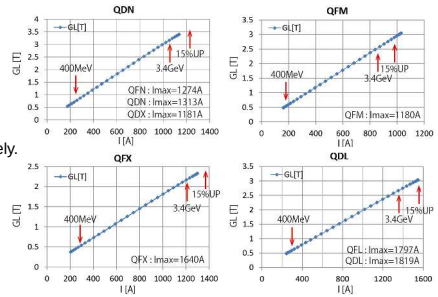
According to the calculation result, DC and AC current are Idc=1919.5A and Iac=1272.5A respectively.
Repetition frequency: 25Hz, magnet inductance: 62mH, turn ratio of choke: 1:2
DC resistance(magnets:32mΩ, choke transformer:24.5mΩ, all cables: 52mΩ)
The power supplies were measured using there parameters.

AC power supply	Max voltage=6196V	⇒	Increased by 6.2%
DC power supply	Max voltage=2811V	⇒	Increased by 5.6%
	Max current=1919.5A	⇒	Increased by 15.1%

The power supply of dipole magnets is being operated already over the rating (+4.7%) due to a saturation so for 3.4GeV extraction, replacement of DC and AC power supply is necessary.

Parameter of the quadrupole magnets of 3GeV RCS

Family Name	Number	Bore Dia. [mm]	N [turn/pole]	Leff [m]	Imax [A]
QFN	12	290	32	0.828	1274
QDN	12	290	32	0.828	1313
QDX	9	290	32	0.828	1181
QFM	3	330	32	1.042	1180
QFX	12	330	32	0.64	1640
QFL	6	410	32	1.072	1797
QDL	6	410	32	1.072	1819



Comparison with the field measurement data of quadrupole magnets

Design current values of quadrupole magnets against extraction energy

Family Name	K1 [1/m]	I [A] 3GeV	3.4GeV	15%UP
QFN	0.2393	964	1067.5	1227.6
QDN	0.2393	964	1067.5	1227.6
QDX	0.21385	861.4	953.9	1097
QFM	0.18424	763.6	845.6	972.5
QFX	0.1611	1087.2	1203.9	1384.5
QFL	0.19433	1208.5	1338.3	1539
QDL	0.19511	1213.4	1343.7	1545.2

GL products and current values are calculated from K1 values.
⇒Power supply fall within the limits of the maximum current.

Comparison with the field measurement data
⇒Although some magnets have no measurement data, it is no problem as they fall in the rated values, in consideration with a 15% allowance.

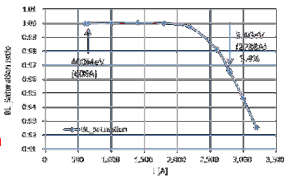
Therefore for quadrupole magnets, it is found out that a 3.4GeV extraction is possible under the current system.

Study on 3.4GeV design of the dipole magnet

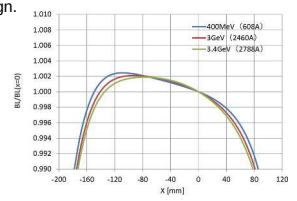
Redesigning is going to be performed on the assumption that new magnets fit in the existing buildings and that a saturation of new magnets falls within 5%. The core length increases by 10% compared to the current design.

Parameter of a Dipole magnet of 3GeV RCS

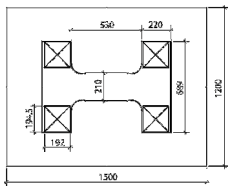
Parameter		Unit	Value
Gap height		[mm]	210
Coil turns		[turn/pole]	36
Bending radius		[m]	11.65
Core length	Straight length	[mm]	2763.5 ⇒3041.3mm
	Arc length	[mm]	2770 ⇒3050mm
Effective length	Straight length	[mm]	3050
	Arc length	[mm]	2946



Saturation property of the current and the integral field of the dipole magnet of 3.4GeV design



Homogeneity of the integral field(TOSCA)



Cross-section shape of the dipole magnet of 3.4GeV design

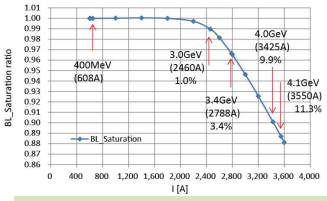
According the calculation result of TOSCA, a saturation of magnets was 3.4%.
An orbit analysis was performed based on the result of a field calculation, it was confirmed that the existing beamline can be used.

Also a rated voltage was calculated from the calculation result.
According to the calculation result, DC and AC current are Idc=1698A and Iac=1090A respectively.
Repetition frequency:25Hz, magnet inductance: 73mH, turn ratio of choke: 1:2
DC resistance(magnets: 33.9mΩ, choke transformer: 33.9mΩ, all cables: 52mΩ)
The power supplies were measured using there parameters.

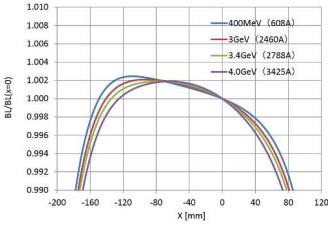
AC power supply	Max voltage=6241V	⇒	Increased by 7%
DC power supply	Max voltage=2567V	⇒	Within the tolerance
	Max current=1698A	⇒	Increased by 2%

For the AC power supply, it is necessary to replace it as an AC rating voltage increases by 7%.
As for the DC power supply, a rating voltage fits into the current specification. Although the rating current increases by 2%, it can be dealt just by changing the control system and the main circuit can be used as it is.

Margin of extraction energy using dipole magnets of 3.4GeV



Saturation property of the current and the integral field of the dipole magnet



Homogeneity of the integral field(TOSCA)

A current value for each energy was decided by changing a coil current density so that an integral field on the central orbit matches to a calculated value in TOSCA.
The field analysis was performed aiming at 10% saturation of magnets.
Above figure shows a calculation result of a saturation property.
An energy size of saturation of magnets to fall within 10% was 4.0GeV.
Saturation at that time was 9.9%.

DC power supply	Max current:		Increased by 21%
AC power supply	Max voltage:		Increased by 62%

Voltage between end terminals of magnets becomes 16kV and an insulation class is upgraded from 6.6kV to 11kV. Therefore a power supply source, a choke transformer, a resonance capacitor and power cables all need to be remanufactured.
According to the result of a field analysis 4.0GeV extraction seems possible, but insulation designing becomes very important.

Design parameter of dipole magnets power supply when extraction energy is enhanced to 4GeV

Parameters		Present Value	4GeV Extruction Value
Injection energy	Einj[MeV]	400	400
Extraction energy	Eext[MeV]	3000	4000
Magnet current	Idc[A]	1654	2017
	Iac[A]	1007	1409
	Imin[A]	647	608
	Imax[A]	2662	3425
	Effective current[A]	1801	2249
	Terminal voltage[V]	9969	16129
Magnet	Inductance[mH]	63	72.9
	DC resistance[Ω] (60℃)	31.8	33.9
Choke transformer	Inductance[mH]	63	63
	DC resistance[Ω] (60℃)	25.7	25.7
Resonance capacitor	Capacitance[uF]	1287	1199
	Terminal voltage[V]	9969	16129
DC power supply	Max voltage[V]	2661	3219
	Max current[A]	1667	2017
AC power supply	Max voltage[V]	5832	9435
	Max current[A]	1587	2568
Power cable	Voltage class[V]	6600	11000
	Cross-section[mm2]	325	325